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MULTIVARIATE ANTHROPOMETRIC MODELS FOR SEATED WORKSTATION DESIGN

Claire C. Gordon

U.S. Army Natick Soldier Center
Natick, Massachusetts, USA 01760-5020

Multivariate statistical methods were used to establish anthropometric design criteria for a seated workstation intended to accommodate 90% of US users. Subjects from an Army database were statistically weighted to match US adult demographic distributions. Eight body dimensions critical to seated workstation design were subject to Principal Components Analysis (PCA), and equal frequency ellipsoids capturing 90% of the subjects were fit to the male and female sample distributions in PCA space. Boundary models located on the ellipsoid surfaces at axis intersections and at midpoints on the ellipsoid traces between axes were used to establish design ranges and limits for operator seating, clearances under the workstation, and work surface heights.

Introduction

Improved ergonomic guidelines for configuring office workstations have challenged product designers to treat a wide variety of components as a single system, and to function effectively in an ergonomic sense, the size, location, and orientation of workstation components must closely relate to the geometry of the user's body. Although experts differ in their concepts of what constitutes optimal user-workstation geometry (e.g. desirable seat pan angles), and individual users differ on what they consider to be comfortable, it is common to estimate ergonomically desirable workstation dimensions using equations based on the user's body dimensions. These equations generally also include constants representing clothing allowances, clearances for comfort, and leeway for postural adjustments. Figure 1 illustrates some body dimensions relevant to workstations and provides equations from Pheasant (1996) relating them to workstation design criteria.

Once the designer has established a particular workstation's concept of use and major functional components, body dimensions are the only unknowns remaining in the equations describing user to workstation relationships. At this point, it is common for designers to refer to tabled percentile values for user body dimensions, and to substitute a 5^{th} percentile value for body dimensions requiring a user minimum or a 95^{th} percentile

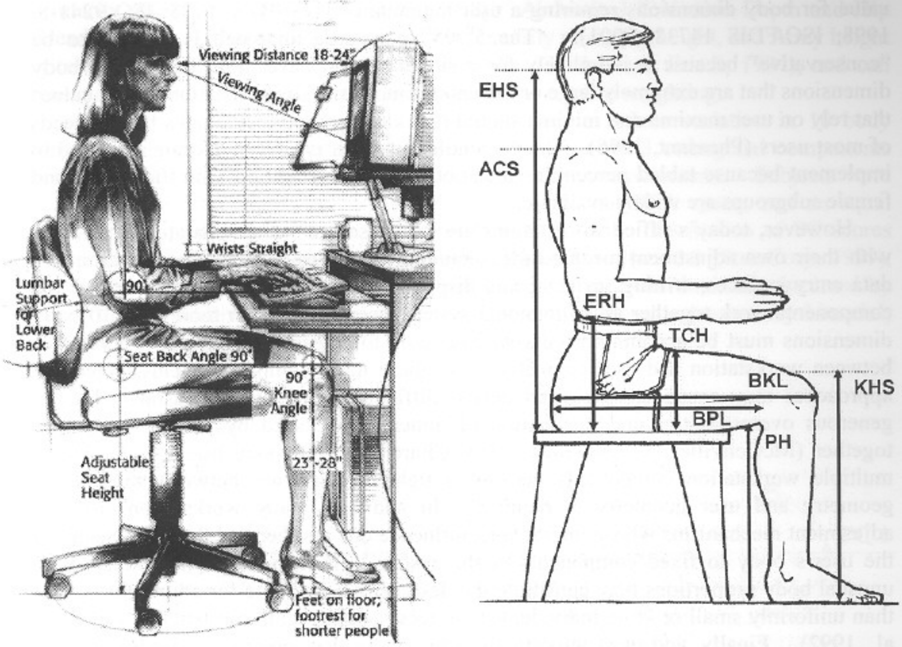

Figure 1. An ergonomic workstation[1] and some relevant body dimensions[2]

Seat Pan Height (***SPH***)	Smallest to Largest **PH** + c (shoe heel) – c (comfort)
Seat Pan Depth	Smallest **BPL** – c (comfort)
Seat Pan Width	Largest **HBS** + c (clothing) + c (leeway to move)
Backrest Top Range	Smallest to Largest **ACS** + c (seat cushion)
Lumbar Support Range	Smallest to Largest **ERH** + c (seat cushion)
Armrest Height Range	Smallest to Largest **ERH** + c (seat cushion)
Input Device Height Range	Smallest to Largest (***SPH*** **+ERH**) + c (seat cushion)
Monitor Height Range	Smallest to Largest (***SPH*** **+EHS**) + c (seat cushion)
Kneehole Clearance Depth	Largest (**BKL-AED**) + $\sqrt{(\mathbf{PH}^2 - \mathbf{SPH}^2)}$ + c (shod foot)
Kneehole Clearance Height	Largest (**PH+TCH**) + c (shoe heel) + c (cushion)

[1] Workstation drawing reproduced with permission of the E.O. Lawrence Berkeley National Laboratory, Berkeley, CA.

[2] Abbreviations: **AED**, Abdominal Extension Depth (not shown); **ACS**, Acromion Height Seated; **BKL**, Buttock Knee Length; **BPL**, Buttock Popliteal Length; **EHS**, Eye Height Seated; **ERH**, Elbow Rest Height; **HBS**, Hip Breadth Seated (not shown); **KHS**, Knee Height Seated; **PH**, Popliteal Height; **TCH**, Thigh Clearance Height. Protocols are published in Gordon *et al* (1989).

value for body dimensions requiring a user maximum (ANSI/HFS, 1988; ISO 9241-5, 1998; ISO/FDIS 14738, 2001). The $5^{th}/95^{th}$ percentile approach is thought to be "conservative" because it is unlikely for a single user to have more than a few body dimensions that are extremely large or extremely small, and so workstation design values that rely on user maxima and minima should provide "generous" estimates for the needs of most users (Pheasant, 1996). The percentile approach is easy and straightforward to implement because tabled percentile values of national user groups and their male and female subgroups are widely available.

However, today's office workstations are comprised of many separate components with their own adjustment mechanisms, including seat pans, seat backs, and armrests, data entry surfaces, writing surfaces, and display support surfaces. To ensure that the components work together as a functional system, user variation in more than 10 body dimensions must be accommodated *simultaneously* to achieve the desired concordance between workstation and user geometry. In these more complex systems, percentile approaches may cause unanticipated design difficulties for several reasons. Firstly, generous overestimation/underestimation of dimensions caused by adding percentiles together (McConville and Churchill, 1976; Churchill, 1978) may not be tolerable in multiple workstation components because a tighter integration between workstation geometry and user geometry is required. In addition, many workstations involve adjustment mechanisms whose interactions influence one another and the relationship of the user's body to fixed components in the system. In such cases, individuals with unusual body proportions may constitute the designer's worst case for adjustment rather than uniformly small or large individuals (e.g. torso heights and limb lengths; Zehner et al., 1992). Finally, and most importantly, when more than one range of adjustment is defined for a single functional system (e.g. seat, armrest, input device, and monitor height), the fact that different body dimensions are not perfectly correlated with one another causes significant reduction in the percentage of users captured by univariate percentile ranges (Moroney and Smith, 1972).

To avoid the problems caused by applying univariate percentiles to functional systems that are multivariate in nature, this paper illustrates an alternative approach developed from earlier work by Bittner (1987) and Zehner (1992) on aviation systems, and by Gordon (1997) on body armor and load carriage systems. Multivariate statistical methods are utilized in the definition of realistic body forms whose dimensions describe the extremes of multivariate body size and shape expected in a centrally located 90% subset of the American population. The body dimensions of these extreme forms are implemented using the equations in Figure 1, and compared with the results achieved by substituting the appropriate 5^{th} and/or 95^{th} percentile values in the same equations. The advantages and disadvantages of this multivariate approach are discussed.

Materials and Methods

Anthropometric data from 5,477 males and 3,469 females measured in the 1988 US Army Anthropometric Survey (Gordon *et al*, 1989) were used in this study. Subjects were weighted prior to statistical analysis to match prevailing US civilian adult age, sex, and race distributions (Gordon, 2000). However, weighting techniques cannot correct for the fact that military body fat and physical fitness requirements preclude overweight individuals from Army samples, whereas overweight men and women are common in the US civilian population. The absence of overweight subjects in the Army database primarily affects two dimensions in this study: Abdominal Extension Depth and Hip Breadth Sitting. Other study dimensions are primarily related to height, and Army height criteria eliminate less than 2% of civilian adults (Gordon and Friedl, 1994), and can reasonably represent civilian distributions after demographic weighting.

Principal Components Analysis (PCA) was used to reduce variation in 10 body dimensions relevant to workstation design (see Figure 1) to 3 orthogonal components comprised of linear combinations of the original body measurements. Subjects were scored on the PCA eigenvectors, plotted in 3-dimensional PCA space, and an equal frequency ellipsoid capturing 90% of subjects was fit to the distribution of PC scores (see Figure 2). All statistical analyses were conducted in Stata 6.0 (StataCorp, 1999), and male and female subjects were analyzed separately to avoid the biases incurred by force-fitting a multivariate normal model over sexually dimorphic (essentially bimodal) distributions (Gordon *et al*, 1997).

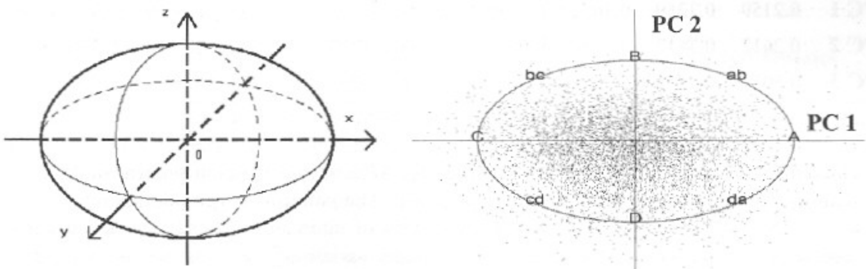

Figure 2. A 3-dimensional ellipsoid and its XY trace

The ellipsoid surface thus represents a 90% accommodation boundary in PCA space. To capture body size and shape extremes represented by the ellipsoid surface, 6 boundary forms are defined at major axis intersections with the surface, and 20 additional forms are located on the surface at arc midpoints using numerical integration. Figure 2 illustrates boundary forms located in the XY (PC1 PC2) plane of the ellipsoid. Once boundary forms are located on the surface of the ellipsoid, the product of their PC scores and eigenvector coefficients are used to determine how far, and in what direction, their body dimensions are located relative to the sample means (Harris, 1975). This process results in a set of 26 extreme forms whose body dimensions are engineering "worst case" scenarios for the 90% of subjects captured by the ellipsoid.

To establish the anthropometric values in the design criteria of Figure 1, the relevant dimensions of each boundary form are substituted in the equations, and statistical software is used to identify the largest and/or smallest values among the 90% boundary forms. In the final step, body dimensions of each subject in the database are compared to the anthropometric limits established using boundary forms. A subject is scored as accommodated only if his/her values are within the design limits for *every* design parameter listed in Figure 1. The proportion of database subjects scored as accommodated in this exercise serves as a check that the design limits derived using boundary forms indeed capture the desired 90% of the user population. Finally, the proportion of subjects captured by the multivariate anthropometric criteria is compared to the proportion of subjects captured if we had substituted 5th and 95th percentile values in the equations in Figure 1.

Results

Results of Principal Components Analysis are presented in Tables 1 and 2. Due to space limitations, only the first 3 PC's are shown and eigenvectors are presented horizontally.

Table 1. Principal Components Analysis of 5,477 males

Component	Eigenvalue	Difference	Proportion	Cumulative
PC 1	4.90161	2.65238	0.4902	0.4902
PC 2	2.24923	0.70385	0.2249	0.7151
PC 3	1.54538	1.11237	0.1545	0.8696

Scoring Coefficients

	AED	AHS	BKL	BPL	EHS	ERH	HBS	KHS	PH	TCH
PC 1	0.2159	0.3259	0.4037	0.3795	0.3125	0.1153	0.3248	0.3900	0.3323	0.2473
PC 2	0.2612	0.3417	-0.2332	-0.2871	0.2409	0.5721	0.1983	-0.2714	-0.3604	0.2236
PC 3	0.5051	-0.3358	0.0896	0.0421	-0.4140	-0.2773	0.3456	-0.0917	-0.2282	0.4405

The first 3 Principal Components accounted for 87% of the variation present in the male sample, and for 86% of the variation in females. The patterns of variable loadings in the sexes were identical: PC 1 (accounting for 49% of male and 47% of female variation) represents overall size; PC 2 (22.5% of male variation; 22% of female variation) contrasts lower limb lengths with trunk heights; PC 3 (15.5% of male variation; 17% of female variation) contrasts breadths and depths with trunk heights. The remaining PC's were not retained because they contributed little additional information to the model.

Table 2. Principal Components Analysis of 3,479 females

Component	Eigenvalue	Difference	Proportion	Cumulative
PC 1	4.72338	2.55678	0.4723	0.4723
PC 2	2.16660	0.46066	0.2167	0.6890
PC 3	1.70594	1.22601	0.1706	0.8596

Scoring Coefficients

	AED	AHS	BKL	BPL	EHS	ERH	HBS	KHS	PH	TCH
PC 1	0.2510	0.2864	0.4197	0.3958	0.3037	0.0758	0.3149	0.4007	0.3066	0.2654
PC 2	-0.0083	0.4860	-0.2162	-0.2473	0.3989	0.6430	0.0850	-0.1861	-0.2007	-0.0338
PC 3	0.5077	-0.1706	0.0110	-0.0788	-0.2226	-0.0011	0.4310	-0.2268	-0.4759	0.4400

Subjects were scored on each of the first 3 PC's using their sex-specific coefficients. Ninety percent ellipsoids centered on the sex-specific mean values were fit to the three-dimensional PCA distributions of male and female subjects. The sex-specific distributions did not completely overlap (see Figure 3), so some male outliers were captured by the female ellipsoid and vice-versa. Together the two ellipsoids captured 92% of the total sample.

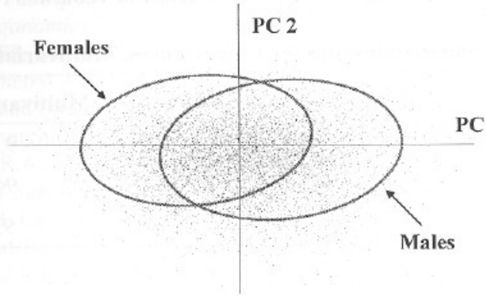

Figure 3. XY Traces of 90% Accommodation Ellipsoids for males and females

As described earlier, body dimensions for each of the 26 boundary forms on the ellipsoid surface were calculated from their PC coordinates and eigenvectors. These boundary forms represent engineering "worst case" scenarios for 90% of male and female users, and they include extremes of body size and of body proportion. To use the boundary forms in estimating the design specifications of Figure 1, each boundary form's body dimensions were substituted into the equations and then analyzed by computer to determine the most extreme design values among the boundary forms. The results of this process are shown below in Table 3, and compared with values derived by substituting the appropriate 5th and/or 95th percentile value in the Figure 1 equations. For comparative purposes, we can ignore the constants representing clothing allowances, comfort space, and compressed seat cushion thickness.

Table 3. Anthropometric Values for Design Specifications, in mm

Design Specification[3]	Multivariate Result	Percentile Result
Seat Pan Height	330 – 484	347 - 472
Seat Pan Depth	421	436
Seat Pan Width	463	450
Backrest Top	497 – 671	514 - 653
Armrest & Lumbar Supports	171 – 294	186 - 280
Input Device Height	543 – 737	560 - 720
Monitor Height	1026 – 1341	1056 - 1307
Kneehole Depth	436	420
Kneehole Height	659	646

[3] For comparative purposes, constants and geometric corrections for seat angle have been ignored. Only anthropometric contributions to the design values are shown.

In the last step of this analysis, theoretical workstation dimensions were computed for every subject in the database using the equations in Figure 1, and the results for each subject were compared against the design criteria derived from boundary form data and univariate percentiles. A subject was scored as accommodated by the design criteria if his or her individual results were within the design limits for *every* design specification in Figure 1. The results of this exercise are shown below in Table 4.

Table 4. Accommodation Rates for Univariate vs. Multivariate Methods

	Percentile Method	Multivariate Method
Males (n=5477)	79.9 %	93.2 %
Females (n=3479)	77.9 %	94.0 %
Total	78.9 %	93.6%

Discussion

As can be seen above, the univariate percentile method is not as conservative as one might have thought. The intended accommodation rate was 90%, and yet only about 80% of workstation users are captured when univariate percentiles for these 10 dimensions were substituted in our workstation design criteria equations. The multivariate method, on the other hand, exceeded the intended 90% accommodation rate, at least in because some of the design criteria required only one-sided limits instead of two-sided ranges.

The multivariate method used here has several advantages. It identifies extreme forms of size and shape that are both realistically proportioned and closely related to the intended accommodation rate of the design. In addition, the anthropometric characteristics of the boundary forms are independent of engineering design details. They describe the extremes of size and shape present in the central 90% of the database population for those body dimensions submitted to the PCA. The designer can change seat cushions, add or remove adjustment mechanisms, change clothing allowances and still use these same extreme forms to establish design criteria, giving true meaning to the term "human centered design".

On the other hand, the multivariate ellipsoid method requires considerable expertise in human biology and biostatistics to exercise fruitfully. The PCA model upon which the ellipsoid is based must capture a large percentage of the variation present in the original design dimensions, and all the critical dimensions must load strongly on at least one of the PC's retained in the model. This requires thoughtful selection of the original body dimensions for consideration, and careful attention to demographic subgroup differences in body size and shape.

Finally, we should note that accurate definition of extreme body sizes and shapes is no guarantee that a design will be successful. Workstation designs that attempt to accommodate poorly correlated body dimensions with a single adjustment mechanism (e.g aircraft and automobile seat rails that use inclines to simultaneously change seat height and proximity to hand/foot controls) require special statistical attention as do adjustment mechanisms that have "stops" at predetermined intervals instead of continuous adjustment. In both cases, accommodating the extremes of size and shape is no guarantee that everyone within the extreme boundaries will be accommodated.

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